

A Method of Dynamic System Identification over Computer Networks

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Abstract

This paper discusses a problem about dynamic system identification over computer networks. A method to identify mathematical models of controlled objects over computer networks is proposed based on modified 1bit delta-sigma transformations and least squares methods for ARX models. The efficacy of the proposed method is verified based on numerical simulations and experiments. In the experiments, mathematical models of a DC motor are identified by using input-output signals of the DC motor over the developed computer network.

Keywords

System Identification; Delta-Sigma Transformation; Least Squares Methods; ARX Models; Computer Networks

Introduction

Recently computer networks such as the Internet have spread quickly and widely. Many researches about applied physics and control engineering have been focused on data transfers in computer networks (Jacobson, 1988)(Low *et al.*, 2002)(Brajendra, *et al.*, 2005)(Meloni *et al.*, 2010). Many congestion controllers have been proposed based on systems and control theories because congestion controllers play an important role in data transfers and the main role is to avoid congestion in the computer networks(Mascolo, 1999) (Hollot *et al.*, 2002)(Quet *et al.*, 2004)(Jin *et al.*, 2005)(Azuma *et al.*, 2006, 2014)(Lestas *et al.*, 2007).

On the other hand, remote control problems over computer networks or communication networks are very interesting issues and have been discussed in many papers (Nilsson *et al.*, 1998)(Giovanni *et al.*, 2010)(Chenbo *et al.*, 2013). In some researches, remote control problems over networks are defined as networked control systems which are called as NCSs (Zhang *et al.*, 2001)(Yue *et al.*, 2005)(Hespanha *et al.*, 2007)(Azuma *et al.*, 2008, 2014). In NCSs, it is assumed that mathematical models of controlled objects are known exactly. If the exact mathematical models of the controlled objects are not obtained, it is difficult to achieve better performances of the controlled systems by using advanced controllers(Mukhopadhyay *et al.*, 1997, 1998). The mathematical models change as time goes on because characteristics and performances of controlled objects also change. If controlled objects have some failures, NCSs become unstable and unsafe. Thus it seems strongly required to estimate or build mathematical models of controlled objects over networks in NCSs. To estimate mathematical models of controlled objects, system identification is well known as one of black box modellings(Ljung, 1987) (Isermann *et al.*, 2010). Recently system identification has been applied to quantum systems (Burgarth *et al.*, 2012).

System identification is largely separated into prediction error methods and subspace identification methods. In the prediction error methods, the prediction error is defined and an optimization problem to minimize the prediction error is considered. The least square method with ARX models is one of the prediction error methods. However some disadvantages of the prediction error methods are known such as bias problems of estimated parameters(Antoulas, 2005). To avoid these disadvantages, the use of prior information of controlled objects has been proposed in system identification(Astolfi, 2010).

By using traditional prediction error methods of system identification, it is possible to estimate mathematical models if suitable input signals and output signals of controlled objects are available in advance. However there is few research about system identification to estimate mathematical models of dynamical systems concerning computer networks. In this paper, this kind of system identification is called as dynamic system identification over

computer networks.

In this paper, dynamic system identification over computer networks is proposed by using modified 1bit delta-sigma transformations with oversampling and the least squares methods for ARX(Auto Regressive eXogenous) models. To achieve better performances of dynamic system identification, modified 1bit delta-sigma transformations have a feedback structure with a proportional gain. By applying modified 1bit delta-sigma transformations, input and output signals are obtained for dynamic system identification. Moreover assuming that mathematical models of controlled objects are described as ARX models, the unknown parameters of the ARX models are estimated by using least squares methods. Finally the effectiveness of the proposed method for dynamic system identification over computer networks is illustrated in simulations and experiments. In the experiments, mathematical models of a DC motor are estimated based on input signals and output signals obtained over the developed computer networks(Azuma *et al.*, 2008, 2014).

Dynamic System Identification over Computer Networks

In this section, a procedure of dynamic system identification over computer networks is proposed. The proposed dynamic system identification consists of modified 1bit delta-sigma transformations with oversampling, decimation and least squares methods with ARX models. Input signals and output signals of identified objects for the proposed dynamic system identification are assumed to be obtained over computer networks.

Modified Delta-sigma Transformation

Usual 1bit delta-sigma transformations are a method to transform continuous signals to 1 bit pulse signals (Candy *et al.*, 1991). However usual 1bit sigma-delta transformations have a problem such that it is difficult to deal with signals whose maximum values are more than 1. To overcome this problem, a modified 1bit sigma-delta transformation(Murahashi *et al.*, 2005) is used in this paper. The modified 1bit sigma-delta transformation is shown in FIG. 1 and has a proportional feedback gain.

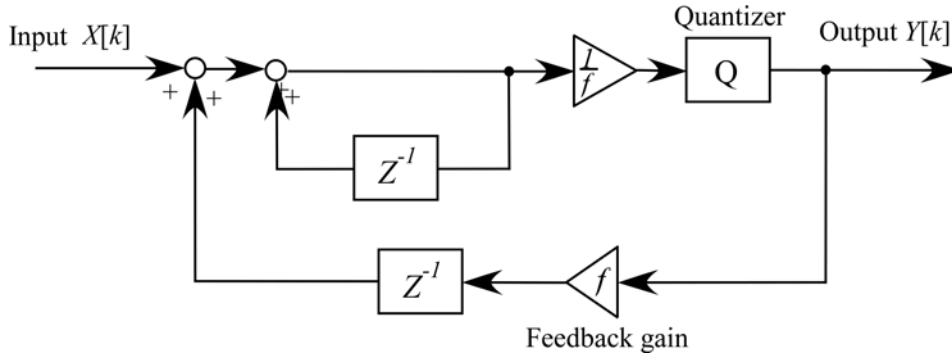


FIG. 1 MODIFIED 1BIT DELTA-SIGMA TRANSFORMATION

In FIG. 1, an input signal is given as $X[k]$ and an output signal is given as $Y[k]$ at a step k . Q is a quantizer approximated as a linear model, z^{-1} is one delay operator and f is a feedback gain. The input- output relationship in FIG. 1 is described as

$$Y[k] = f^{-1}X[k] + (1 - Z^{-1})N_q[k],$$

where $N_q[k]$ is a quantization error at the step k . By using the modified 1bit delta-sigma transformation, the output signal is restricted as $-1 \leq Y[k] \leq 1$. Thus the

condition $-f \leq X[k] \leq f$ is satisfied. Therefore if $f > 1$ is satisfied, then the maximum value of the input signal becomes more than 1.

System Identification over Computer Networks

Now a dynamic system identification method over computer networks is proposed. Here we assume that input or output signals of the identified objects are available in advance through computer networks. The procedure of the proposed method is described as follows,

Step 1. Sampling: Oversampling of input signals and output signals.

Step 2. Quantization: Application of the modified 1bit delta-sigma transformation with a feedback gain f to the oversampled input and output signals.

Step 3. Decimation: Cancellation of noises which are quantization errors by using low pass filters.

Step 4. Reconstruction: Multiplication of the decimated input-output signals by the feedback gain f .

Step 5. Dynamic system identification: Applying the least squares method to the ARX model.

This procedure from step 1 to step 5 is depicted in FIG. 2. Original input and output signals are converted to special signals($y[k], u[k], k=1,2,\dots, N$) for dynamic system identification through step 1 to step 4. Step 5 is summarized as the next paragraph.

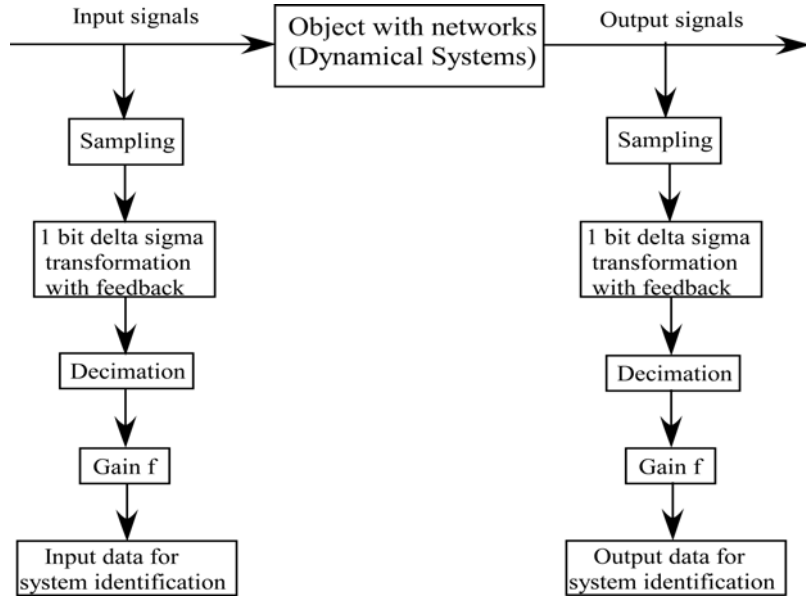


FIG. 2 THE PROPOSED PROCEDURE(STEP 1 to STEP 4)

The following ARX model with input time-delays is considered.

$$\begin{aligned} A(q)y[k] &= B(q)u[k] + w[k], \\ A(q) &= 1 + a_1q^{-1} + a_2q^{-2} + \dots + a_{n_a}q^{-n_a}, \\ B(q) &= b_1q^{-(n_k+1)} + b_2q^{-(n_k+2)} + \dots + b_{n_b}q^{-(n_k+n_b)}. \end{aligned} \quad (1)$$

where q is an irreducible shift operator, w is a white noise and $a_k(k=1,2,\dots,n_a)$, $b_k(k=1,2,\dots,n_b)$ are unknown parameters. The parameters n_a , n_b are the polynomial order of the ARX model and the parameter n_k is the input time-delay. Introducing the following unknown vector

$$\theta = [a_1 \quad \dots \quad a_{n_a} \quad b_1 \quad \dots \quad b_{n_b}]^T,$$

and the following regression vector

$$\phi[k] = [-y[k-1] \quad \dots \quad -y[k-n_a] \quad u[k-(n_k+1)] \quad \dots \quad u[k-(n_k+n_b)]]^T,$$

then the output $y[k]$ in the equation (1) is described as follows,

$$y[k] = \theta^T \phi[k] + w[k]. \quad (2)$$

Because the estimated output is equal to $\theta^T \phi[k]$ from the equation (2), the estimated error is defined as

$$e[k, \theta] = y[k] - \theta^T \phi[k].$$

Thus defining the performance index as

$$J_N(\theta) = \frac{1}{N} \sum_{k=1}^N e[k, \theta]^2,$$

the unknown vector θ can be estimated based on the least squares method. The estimated vector is derived as follows,

$$\begin{aligned} \hat{\theta} &= \min_{\theta} J_N(\theta) = R^{-1}(N)F(N), \\ R(N) &= \frac{1}{N} \sum_{k=1}^N \phi[k]\phi^T[k], \\ F(N) &= \frac{1}{N} \sum_{k=1}^N y[k]\phi[k]. \end{aligned} \tag{3}$$

It is possible to apply the other well-known optimization methods such as GA or PSO for the estimation problem of the unknown vector θ . Because those optimization methods are based on numerical computations, the solutions are not assured to be exactly optimal. However by using the least squares method, the optimal vector $\hat{\theta}$ is assured to be theoretically optimal.

Simulation Result

To demonstrate the proposed method, we assume that output signals are available through a network with bit error and input signals are available directly. Moreover we assume that there exists the network after step 2 and the bit error influences the over sampled output signals at step 3.

The transfer function of the identified object is considered as a first order system described as

$$G(s) = \frac{130}{0.15s + 1}.$$

The input signal is a white noise with the mean value 0 and the variance 0.01. The sampling period is 25ms and the oversampling period is 0.25ms. The feedback gain for input signal is $f_u=1.5$ and the feedback gain for output signal is $f_y=40$ in the modified 1bit delta-sigma transformation. The polynomial order of the ARX model is $n_a=n_b=2$ and the input time-delay is $n_k=0$. The dimension of decimation is 100 and Chebyshev filter is used as a low pass filter.

The performance of the identification is measured as the fitting ratio defined as follows,

$$Fit = \left(1 - \frac{\sqrt{\sum_{k=1}^N (\hat{y}[k] - y[k])^2}}{\sqrt{\sum_{k=1}^N (\bar{y} - y[k])^2}} \right) \times 100,$$

where $\hat{y}[k]$ is the output of the estimated ARX model and $\bar{y}$ is the average value of the original output signal defined as

$$\bar{y} = \frac{1}{N} \sum_{k=1}^N y[k].$$

This value is called as normalized root mean square errors. The simulation result is shown in FIG. 3. In FIG. 3, the horizontal axis is a bit error rate in considered networks and the vertical axis is a fitting ratio. The blue solid line denotes the fitting ratio by using the proposed method and the red dashed line denotes the fitting ratio by using the traditional system identification method with pulse code modulation instead of the modified 1bit deltasigma transformation in step 2. In case of the bit error=0%, the results of the proposed method and traditional method are same and the fitting ratios are $Fit=100\%$.

The fitting ratio using the proposed method decreases linearly as the bit error rate increases. However the fitting ratio using the traditional method decreases drastically as the bit error rate increases. Thus the performance of the proposed method is better than that of the traditional method. Moreover this simulation result shows that the

proposed method is especially effective in case that bit error occurs in the network. This kind of bit error is often appeared in wireless communication networks.

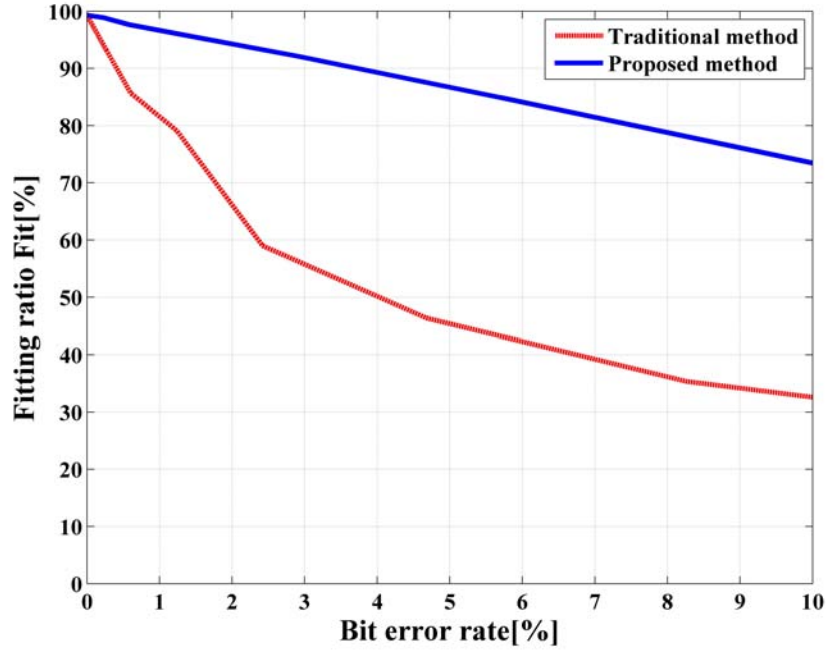


FIG. 3 FITTING RATIOS(SIMULATION)

Experimental Results Using the Developed Computer Network

Setting of the Experiment

The experimental environment is shown in FIG. 4. FIG. 4 shows the developed computer network and two rooms connected with LAN cables(Azuma *et al.*, 2008, 2014). There is a computer which is called as PC for system identification in the room 1. The tasks of PC for system identification is to obtain the input signals and the output signals of an identified object through the developed computer network and to identify the mathematical model of the object. Moreover three computers are placed in the room 2. Two computer are a router and a PC to occur congestion in the developed computer network respectively. The other computer is called as Sender/Receiver PC and this is an interface computer from an I/O electronic circuit to control a DC motor. The I/O electronic circuit is shown in FIG. 5. The DC motor is the identified object in this experiment. The input signal is the voltage and the output signal is the rotation speed.

The network setting is given as follows,

- PC for system identification and the router are linked by a 10 Based-T LAN cable.
- The router and Sender/Receiver PC are linked by a 100 Base-T LAN cable.

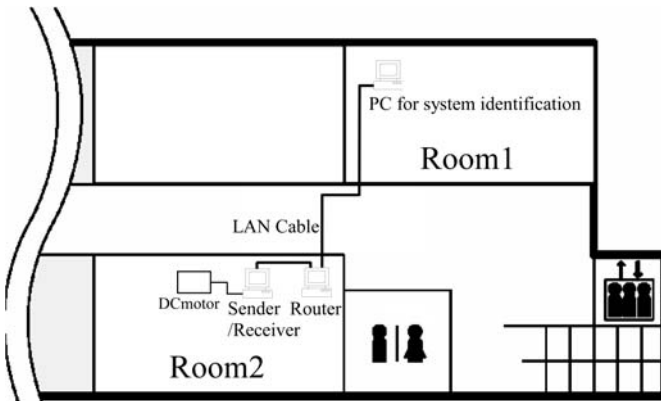


FIG. 4 EXPERIMENTAL ENVIRONMENT

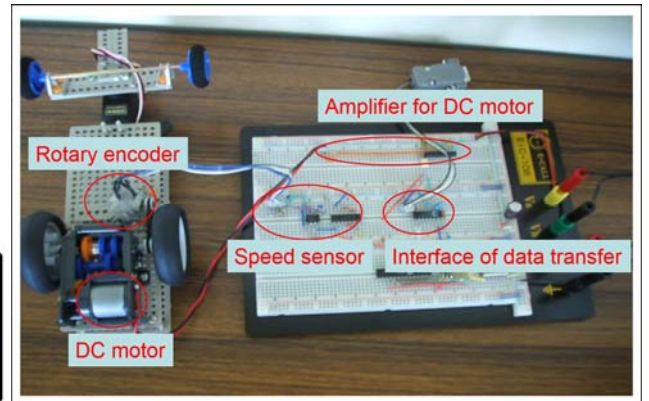


FIG. 5 DC MOTOR AND I/O CIRCUIT

Local Experiment

To show the efficacy of the proposed method, a local experiment is performed. The local experiment means that the Sender/Receiver PC and the PC for system identification are removed and a mathematical model of the DC motor is identified directly by using the usual system identification method based on the least squares method and the ARX model. From this local experiment, the reference mathematical model of the DC motor can be obtained.

First the following conditions are considered in this experiment.

Condition 1: The input signal is given as a pseudo random binary signal from -1.0V to +1.0V.

Condition 2: The sampling period is 25ms.

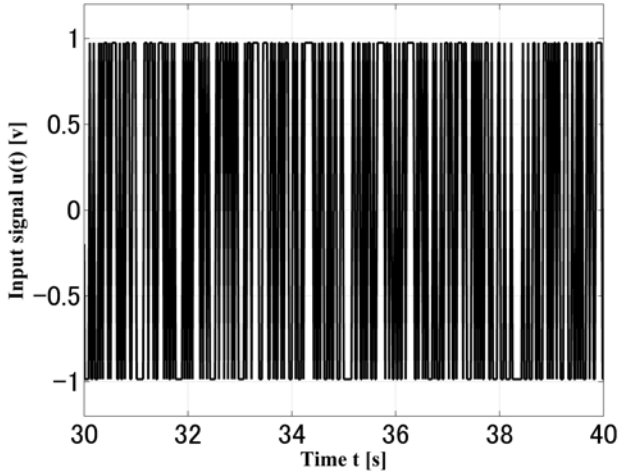


FIG 6 INPUT SIGNAL (LOCAL EXPERIMENT)

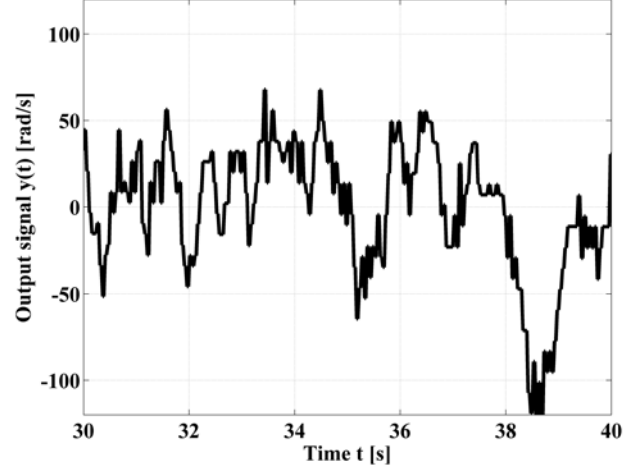


FIG 7 OUTPUT SIGNAL (LOCAL EXPERIMENT)

FIG. 6 shows the input signal $u(t)$ of the DC motor from 30s to 40s. This figure shows that this is a pseudo random binary signal from -1.0V to +1.0V. FIG. 7 shows the output signal $y(t)$ from the DC motor from 30s to 40s. The output signal is the rotation speed of the DC motor.

Secondly the sampled input signal $u[k]$ and the sampled output signal $y[k]$ are obtained based on FIG. 6 and FIG. 7. By using MATLAB, $n_a=3, n_b=3, n_k=3$ are computed as optimal values which minimize a loss function. The loss function is given as the Akaike's Information Criterion (AIC). The mathematical model of the DC motor is obtained as the following ARX model.

$$\begin{aligned} A(z)y[k] &= B(z)u[k] + w[k], \\ A(z) &= 1 - 0.585z^{-1} + 0.086z^{-2} - 0.389z^{-3}, \\ B(z) &= 7.042z^{-3} + 6.432z^{-4} + 3.971z^{-5}. \end{aligned} \quad (4)$$

Experiment over the Developed Computer Network

Next the experiment over the developed computer network is discussed. Considering FIG. 4, the input signals and the output signals of the DC motor can be obtained over the network at the PC for system identification. Experimental conditions are same as condition 1 and condition 2. Moreover the next conditions are considered to applying the modified 1bit delta-sigma transformation to the input and output signals.

Condition 3: The oversampling period is 0.25ms.

Condition 4: The feedback gain for input signal is $f_u=1.0$ and the feedback gain for output signal is $f_y=120$ in the modified 1bit delta-sigma transformation.

Condition 5: The dimension of decimation is 100 and Chebyshev filter is used as the low pass filter.

Considering condition 1 to 5 and applying step 1 to 4 in the proposed method, FIG. 8 and FIG. 9 are obtained as the modified input and output signals. Here note that the modified input signal $u[k]$ in FIG. 8 is largely different from the input signal in FIG. 6 and the modified output signal $y[k]$ in FIG. 9 is a little different from the output signal in

FIG. 7. By using MATLAB, $n_a=3, n_b=3, n_k=3$ are obtained as optimal values which minimize the AIC. The mathematical model of the DC motor is computed as the ARX model in the equation (5). Although the dimensions of ARX models are same, the estimated parameters are different from that of the equation(4).

$$\begin{aligned} A(z)y[k] &= B(z)u[k] + w[k], \\ A(z) &= 1 - 0.840z^{-1} + 0.406z^{-2} - 0.4721z^{-3}, \\ B(z) &= 6.865z^{-3} + 4.735z^{-4} + 4.267z^{-5}. \end{aligned} \quad (5)$$

To compare the ARX models in the equations (4) and (5), the frequency response is shown in FIG. 10. In FIG. 10, the blue solid line denotes the frequency response of the equation (5). The black dashed line denotes the frequency response of the equation(4). Almost same results are obtained at low frequency area however the results are a little different between 10Hz and 20Hz. Based on FIG. 9, the identified ARX models in the equation (4) and (5) are almost same.

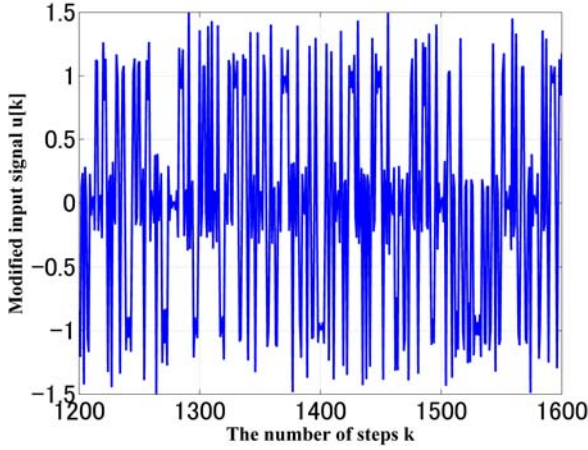


FIG 8 MODIFIED INPUT SIGNAL BY PROPOSED APPROACH

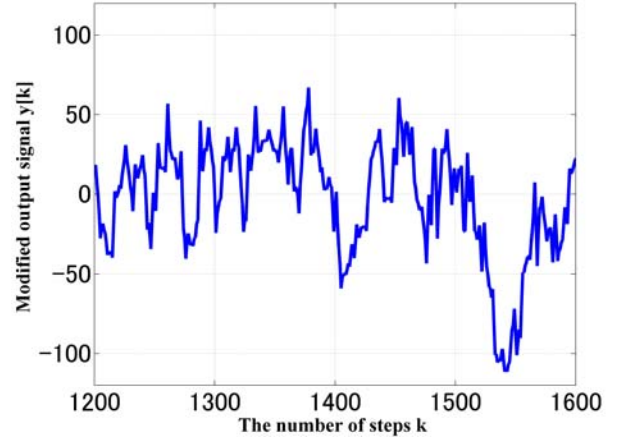
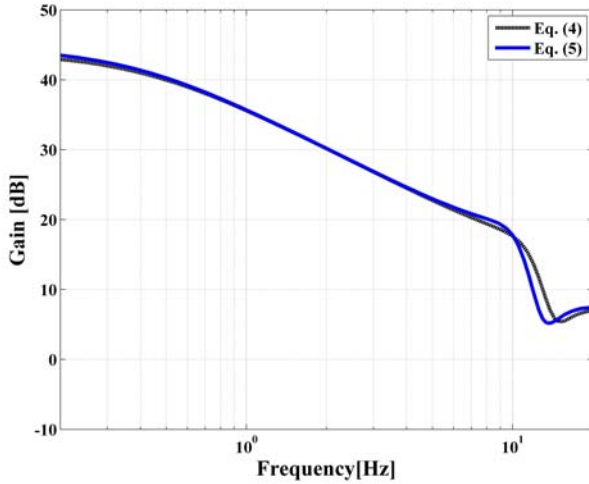
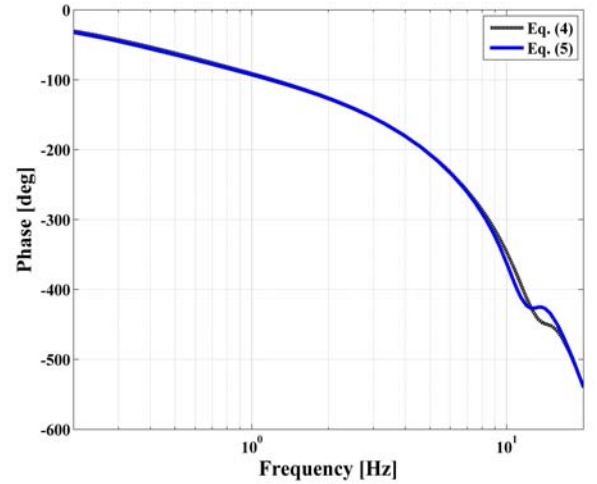


FIG 9 MODIFIED OUTPUT SIGNAL BY PROPOSED APPROACH



(a)MAGNITUDE PLOT



(b)PHASE PLOT

FIG 10 FREQUENCY RESPONSE

Finally the time responses of the ARX models in the equations (4) and (5) are shown in FIG. 11. In FIG. 11, the green chained line denotes the measured output of the DC motor for a pseudo random binary input signal. The back dashed line denotes the output of the equation (4) for same pseudo random binary input signal. The blue solid line denotes the output of the equation (5) for same pseudo random binary input signal. The output of (4) is almost same as that of (5).

However the normalized root mean square error is calculated as 65.02% between the measured output and the output of the equation (4). Moreover the normalized root mean square error is calculated as 66.63% between the measured output and the output of the equation (5). It can be seen that the fitting ratio is improved by using the

ARX model in the equation (5). Therefore the proposed method achieves a better performance than the traditional method for dynamic system identification over computer networks.

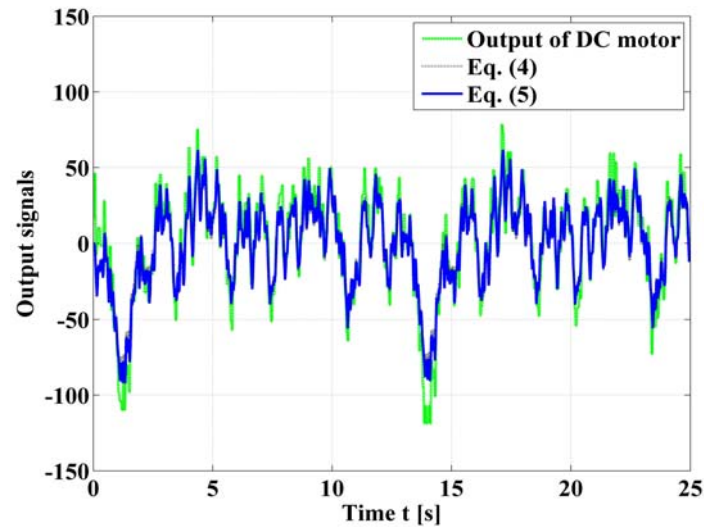


FIG 11 TIME RESPONSE

Conclusions

In this paper, a problem to build the mathematical model of identified objects over computer networks has been considered and a method has been proposed based on modified 1bit delta-sigma transformations and least squares methods using ARX models. The effectiveness of the proposed method is demonstrated in numerical simulations and experiments. From simulation results, it has been seen that the proposed method is very effective for dynamic system identification over computer networks where bit error occurs. In experimental results, it has been verified that the proposed method is more effective than a usual method for dynamic system identification over computer networks. Especially the fitting ratio of time responses can be improved by using the proposed method.

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